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Review

Development of an integrated sustainability matrix to depict challenges and trade-offs of introducing bio-based plastics in the food packaging value chain

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ABSTRACT

As global plastic pollution is gaining increased attention, the use of bio-based plastics, especially in the food packaging sector, is growing in popularity. While this move is regarded as a solution to plastic pollution, it may shift or create detrimental impacts elsewhere in the production, consumption, management system, a possibility that is underexplored. The aim of the present study is to identify the potential challenges and trade-offs associated with the introduction of bio-based plastics in the food packaging industry, and highlight issues relevant to policy and decision-making processes. We employ a whole system approach to review the literature and assess holistically the performance of bio-based plastics, which looks at the entire lifecycle of bio-based plastic packaging (i.e. production, consumption, management) and considers wider aspects in the environmental, economic, social and technical sustainability domains. Based on our findings, we developed, and present herein, a sustainability decision matrix, a novel guiding tool, which can provide important insights into the potential impacts of the introduction of larger amount of bio-based plastic food packaging in the future and support decision-making processes. In conclusion, our preliminary high-level assessment of the bio-based plastics production, use and management system clearly reveals a number of blind-spots across the entire system that are currently ignored by the use of single-dimensional approaches. This highlights that the sustainability assessment of specific bio-based polymers requires thorough and further research that takes into account the type of feedstock, infrastructure availability, and interactions between sustainability domains, to ensure that the substitution of petrochemical-based plastics with bio-based alternatives in food packaging sector will not lead to unintended consequences.

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Nomenclature

bio-PE	Bio-based polyethylene
bio-PET	Bio-based polyethylene terephthalate
bio-PP	Bio-based polypropylene
CF	Carbon footprint
CH_4	Methane
CO_2	carbon dioxide
CVORR	Complex value optimisation for resource recovery
EoL	End-of-life
GDP	Gross domestic product
GHG	Greenhouse gas
GMO	Genetically modified organisms
GWP	Global warming potential
IAS	Intentionally added substances
LCA	Life cycle assessment
Mt	Million metric tonnes
MRF	Material recovery facility
NIAS	Non-intentionally added substances
NH_3	Ammonia
NOx	Nitrous oxides
PBAT	Polybutylene adipate-*co*-terephtalate
PBS/A	Polybutylene succinate/adipate
PCL	Poly caprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Poly-hyroxy-alkanoates
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PUD	Polyurethane dispersions
RRfW	Resource recovery from waste

1. Introduction

The size of the food packaging market is expected to rise from 303.3 to 456.6 USD billion over the period 2019–2027, a compound annual growth rate (CAGR) of 5.2% (GVR, 2020), with plastics being the most prevalent packing materials after paper and cardboard (Eurostat. Packaging waste, 2020). The benefits of plastic packaging are widely documented (e.g., lightweight, durable, flexible, strong, corrosion-resistant, convenient, cheap) making them particularly attractive for use in many sectors (Storz and Vorlop, 2013; Robertson, 2012). However, plastic packaging has recently received significant scientific and public attention due to its ubiquitous presence in terrestrial and marine environments as a pollutant released from inland and coastal communities, recreational activities and lost goods from shipping (Hahladakis, 2020; Jambeck et al., 2015; Law, 2017; Iacovidou et al., 2020). Marine plastic pollution is widespread, with plastic debris found in the artic sea ice (Obbard et al., 2014), sea surface, and sea floor (Schlining et al., 2013). The total amount of mismanaged plastics to have entered the earth's oceans is estimated anywhere between 0.5 and 12.7 million metric tonnes (Mt) (Jambeck et al., 2015; Tramoy et al., 2019), and the scale and intensity of plastic pollution appears to be caused largely by plastic packaging waste that is accidentally, deliberately, illegally or uncontrollably released to the environment (Iacovidou et al., 2020). This has driven demand for new and innovative packaging solutions. Current commercial applications and future trends of different types of food packaging technologies have been described in (Han et al., 2018).

Bioplastics have gained increased popularity in the plastics manufacturing industry as a way to increase their sustainability credentials and curb plastic pollution. The term 'bioplastics' is commonly used to refer to both the *bio-based origin* of a plastic and/or its *biodegradable character*. While *bio-based* plastics are according to the European Standard EN 16575 (EN 16575 2014), those derived from plant-based materials (also known as biomass[1]) (Iacovidou and Gerassimidou, 2018; Hahladakis et al., 2020), it is not only *bio-based* plastics that are *biodegradable*, and not all types of *bio-based* plastics are *biodegradable* (Iacovidou and Gerassimidou, 2018). It is therefore necessary to define and disambiguate the vocabulary surrounding bio-plastics. According to the International Union of Pure and Applied Chemistry (IUPAC) biodegradability refers to the susceptibility of a polymer to degradation by biological activity (e.g. broken down by microorganisms such as bacteria or fungi) accompanied by a lowering of its molar mass, into producing environmentally acceptable substances with desirable properties (e.g. water, carbon dioxide (CO_2), methane (CH_4) and biomass (Horie et al., 2004)). The biodegradability property can apply to both bio-based and petrochemical-based materials. As a result, the term bioplastics is used to refer to: biodegradable and non-biodegradable bio-based plastics, and petrochemical-based biodegradable plastics.

In relation to the bio-based origin, threshold values of renewable content that mark a material to be called bio-based can be found in national regulations, but there is no a general agreement on a specific reference limit (Bioplastics, 2020). For example, the USDA BioPreffered Program determined a wide range of minimum acceptable bio-based content, 7–95%, depending on product

[1] Biomass refers here to any material of biological origin, excluding those from geological formations or fossilized materials, that is considered to be 'carbon neutral' and can be renewable.

category factors (USDA, 2011). However, there are standardised labels that indicate the biomass content of bio-based materials provided by certifiers, such as DIN CERTCO and TÜV AUSTRIA Belgium (Bioplastics, 2020).

There are now numerous types of bioplastics used in food and drink packaging applications (e.g., coffee pods, cups, and food waste bags) amounting to 53% of the global bioplastics demand in 2019, with small amounts used in other sectors, e.g., consumer electronics, automotive, agriculture/horticulture, toys and textiles (Bioplastics, 2019a). In 2019, the total amount of bioplastics placed on the market was 2.11 Mt, and Europe was the largest regional consumer of bioplastics (Bioplastics, 2019a). Nonetheless, Europe contributed only to a quarter of the global bioplastics production in 2019, following China which was the major producer (45%) (Bioplastics, 2019a). The bio-based fraction of bioplastics are commonly made of carbohydrate-rich plants such as corn or sugar cane, so called food crops or first (1st) generation feedstock, but they can also be made from second (2nd) and third (3rd) generation feedstocks, which are materials not suitable for human and animal consumption, e.g. cellulosic by-products (e.g., straw, corn stover or bagasse), and biomass waste (non-food feedstock) (Bioplastics, 2019a; Spierling et al., 2018a; Markl et al., 2018; Ögmundarson et al., 2020a). To date, 1st generation feedstocks are currently the most suitable for bio-based plastics production that reaches commercialization levels (Bioplastics, 2019a; Ögmundarson et al., 2020a).

Bio-based plastics are increasingly growing in popularity, yet there is an imminent challenge with their use. Investments in new production processes that envisage to boost bioplastics demand and reduce their production cost in the future are made without validating bio-based plastics sustainability potential (Research eu.,Bioplastics: Sustainable materials for building a strong and circular European bioeconomy, 2018). This can jeopardize the sustainability of the production, consumption and management of bio-based plastics in the long-term, which still remains inconclusive despite the numerous studies in this area. The transition towards bio-based economy is surrounded by a high degree of complexity and uncertainty across the entire lifecycle (Falcone and Imbert, 2019). Many scholars have considered the sustainability potential of bioplastics at only one or two stages of the their lifecycle (Storz and Vorlop, 2013; Falcone and Imbert, 2019) or they may have focused on the environmental life cycle sustainability performance of bioplastics, using life cycle assessment (LCA) (Iacovidou and Gerassimidou, 2018; Ögmundarson et al., 2020a; Changwichan et al., 2018; Koch and Mihalyi, 2018; Bier et al., 2011; Spierling et al., 2018b; Thakur et al., 2018; Ashok et al., 2016; Dietrich et al., 2017; Ögmundarson et al., 2020b; Ögmundarson et al.), placing little attention on their social and economic performance. A number of studies have investigated different strategies to produce and improve the performance of bioplastics (Peelman et al., 2013; Cabedo et al., 2006; Amin et al., 2019; Aguilar et al., 2019; Minakawa et al., 2019; Rodriguez-Perez et al., 2018; Chen, 2010), while others have focused on assessing the end-of-life (EoL) management practices of a wide range of bioplastics, trying to elucidate their biodegradability (Rujnić-Sokele and Pilipović, 2017; Kaeb, 2016; Kershaw et al., 2015) and/or recyclability potential (Soroudi and Jakubowicz, 2013; Shah et al., 2012; Tsuneizumi et al., 2010; Faisal et al., 2006). Only a few studies have attempted to conceptually assess bioplastics sustainability performance over their entire life cycle (Spierling et al., 2018b; Ögmundarson et al.). Even though these studies are insightful with regards to the environmental and economic impacts of bioplastics, they remain inconclusive on the performance of bioplastics from a multidimensional perspective that spans environmental, economic, societal and technological aspects.

Recognizing the tremendous importance of filling this gap, this article analyses the existing literature on bio-based plastics used in the food packaging sector, and outlines environmental, economic, social and technical impacts from a systems perspective. By focusing on all stages of bioplastics lifecycle, from feedstock extraction to EoL management, we identify the challenges and trade-offs associated with the use of bio-based plastics along the entire food packaging value chain. This work focuses specifically on biodegradable and non-biodegradable bio-based plastics made of 1st generation feedstock, exploring some of the multidimensional implications of their use in replacing petrochemical-based plastics. This effectively excludes from our analysis biodegradable petrochemical-based plastics, and bio-based plastics produced from 2nd and 3rd generation feedstocks, of which commercial presence is currently limited (Brodin et al, 2017), to both diffuse potential confusion and additional complexity arising from the literature on these types of bioplastics (van den Oever, 2017). The ultimate aim of this work is to populate a sustainability decision matrix that encompasses all aspects associated with the emergence of bio-based plastics in the food packaging sector and their sustainability potential, be that environmental, economic or social. This systemic analysis is both timely and necessary, and the sustainability matrix is intended to be applied as a guiding tool to examine the sustainability performance of specific bioplastic applications across their life cycle. Developing this understanding is necessary to underpin informed decision-making processes and drive sustainability in the food packaging sector.

2. Methodology

A literature review was carried out to collect information with regards to the environmental, economic, social and technical aspects associated with the use of bio-based plastics in the food packaging sector. In Table 1, plastics are classified into four main categories based upon their biodegradability status and the material from which they are derived.

To avoid any misinterpretation, we developed the following coding when discussing on the different groups of plastics in the next Sections:

- Bio-based plastics (**Column 2**) include both biodegradable (**Column 2, Row 2**) and non-biodegradable plastics (**Column 2, Row 3**);
- Biodegradable plastics (**Row 2**) refer to both bio-based (**Column 2, Row 2**) and petrochemical-based plastics (**Column 3, Row 2**);
- Bioplastics refer to bio-based plastics (**Column 2, Row 2** & **Row 3**), and petrochemical-based biodegradable plastics (**Column 3, Row 2**);
- Petrochemical-based plastics (**Column 3**) include both biodegradable (**Column 3, Row 2**) and non-biodegradable (**Column 3, Row 3**) plastics.

The information collected, was necessarily organised and analysed based on the bio-based plastics lifecycle, adapting the simplified resource recovery from waste (RRfW) system configuration presented in (Iacovidou et al., 2017a).

2.1. Literature review

The literature search strategy addressed two main research questions: 1) overall description of the emergence of bio-based plastics (**Column 2**); and 2) multidimensional value description – referring to environmental, economic, technical and social positive and negative impacts of bio-based biodegradable (**Column 2**, **Row 2**) and non-biodegradable plastics (**Column 2, Row 3**) placed on the

Table 1
Classification of plastics based on raw material origin and biodegradability. The shaded area indicates the so called 'bioplastics'; the columns and rows numbering and colour are used as a system of communication in the text.

	Column 2 Bio-based plastics	Column 3 Petrochemical-based plastics
Row 2 **Biodegradable plastics**	Polylactic acid (PLA) Polyhydroxyalkanoate (PHA) Polysaccharide derivatives Polybutylene succinate (bio-PBS)	Poly caprolactone (PCL) Polybutylene succinate/adipate (PBS/A) Polybutylene adipate-*co*-terephtalate (PBAT)
Row 3 **Non-biodegradable plastics**	Polyol-polyurethane Bio-based polyethylene (bio-PE) Bio-based polyethylene terephthalate (bio-PET)	Polyethylene terephthalate (PET) Polyethylene (PE) Polyvinyl chloride (PVC) Polypropylene (PP) Polystyrene (PS) Polycarbonate (PC)

market across the value chain. The literature databases Scopus, Web of Science and Google Scholar were queried using several combinations of keywords such as "bioplastics", "bio-based plastics", "sustainability", "circular economy", "environmental impact", "economic/financial impact", "cost", "social impact", "technical impact", "bioplastic feedstock", "land use change", "global warming potential" and "GWP", "end of life" and "EoL", "options", "bioplastic properties", "eco-efficiency", "life cycle assessment" and "LCA", and "plastic packaging".

The retrieved literature was screened for two main eligibility criteria to include only records that focused on: i) 1st generation bio-based plastics (**Column 2**) such as wheat, cereal or sugarcane as raw material for the bio-based plastics production; and ii) bio-based plastics that are commercially available in the food packaging industry. Additional searches were carried out where necessary and relevant to further decipher specific aspects of interest identified at this first stage.

2.2. *Organizing principles for the sustainability matrix development*

The information collected from our literature review was organized according to the main lifecycle stages of the bio-based plastics introduced in the food packaging system, regardless of whether these are biodegradable (**Column 2**, **Row 2**) or non-biodegradable (**Column 2**, **Row 3**). At each stage of lifecycle, the sustainability performance of bio-based plastics (**Column 2**) was described from a multidimensional perspective using the CVORR approach (description of which can be found elsewhere (Iacovidou et al., 2017b; Iacovidou et al., 2020)), and using the information collected in Section 2.1, indicating the main critical aspects that need to be considered. Fig. 1 illustrates a simplified depiction of the main stages involved in the bio-based plastics production-use-management system.

Each of the illustrated crude stages (Fig. 1), involve a number of processes, as follows:

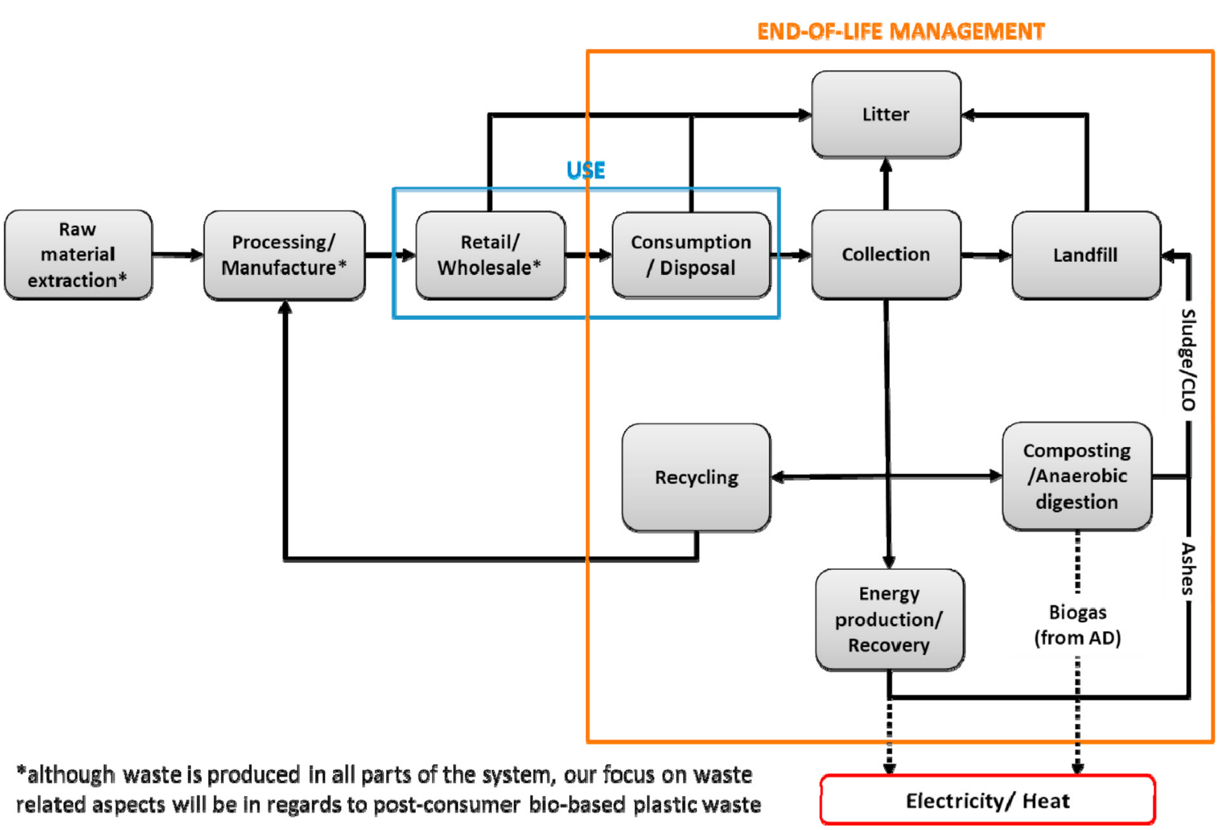

Fig. 1. Lifecycle of bio-based biodegradable (**Column 2, Row 2**) and non-biodegradable (**Column 2, Row 3**), including all potential EoL options implemented globally (adapted from (Iacovidou et al., 2017a)).

- *Raw material (feedstock) extraction*, refers to the processes involved in feedstock (i.e. agricultural crops) cultivation and harvesting;
- *Processing/Manufacture*, refers to a series of steps that include feedstock pre-treatment, biorefinery and polymerisation, including also the design and processing of material into a pre-from and final product manufacture;
- *Use*, refers to stocking and availability of packaging products made of bio-based plastics (**Column 2**) by retailers/wholesalers, the product purchase and use by consumers (end-users), and its

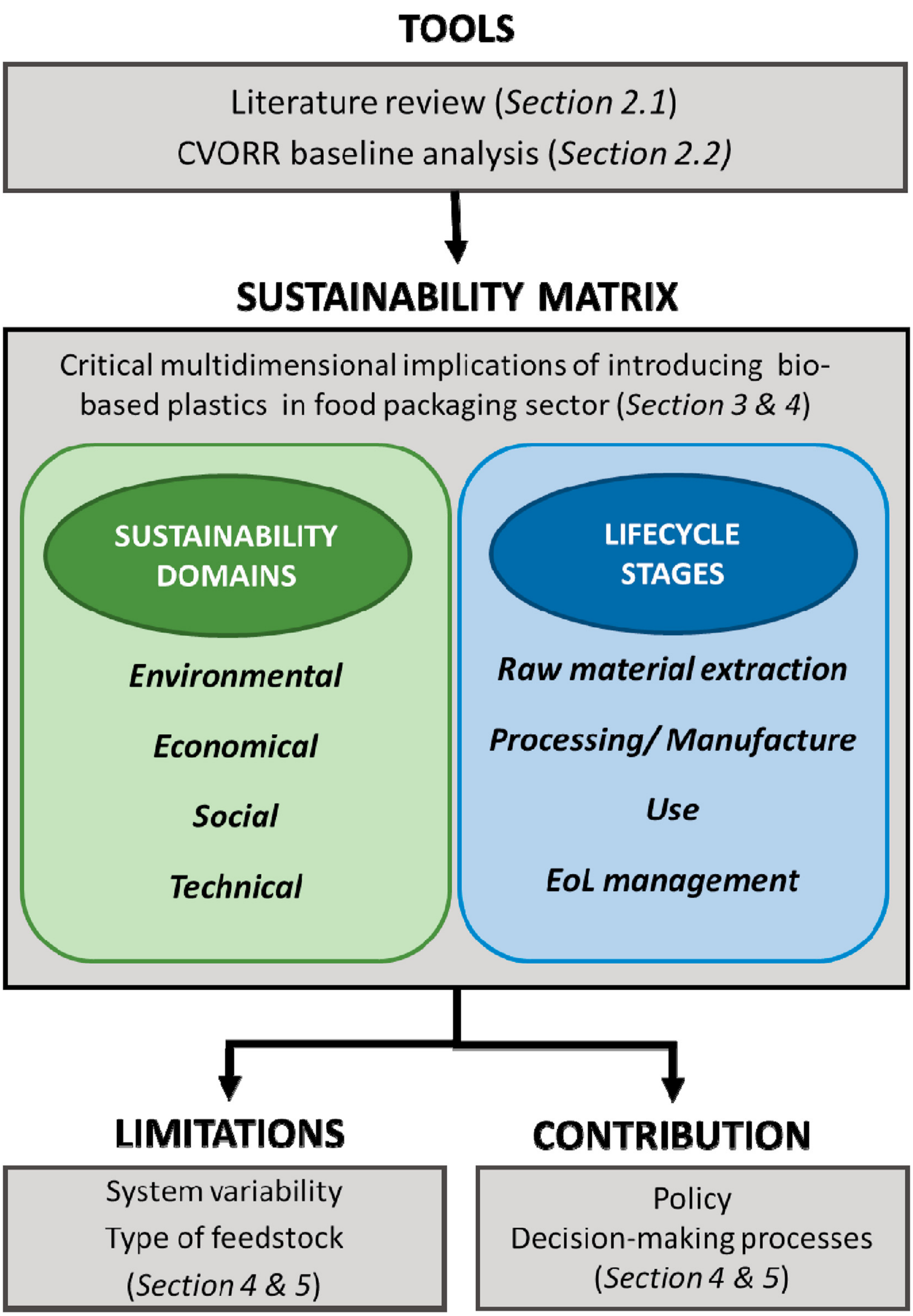

Fig. 2. Methodological overview of the present study: development of a holistic sustainability matrix to identify critical challenges and trade-offs associated with the replacement of conventional plastics with bio-based in food packaging sector.

final disposal as waste into receptacles (or not) in the household and on-the go;
- *EoL management*, refers to the suite of options available for bio-based plastic (**Column 2**) packaging waste management, which depends largely on its method of disposal and involves the collection, transport and management via recycling, composting, anaerobic digestion, incineration (with or without energy recovery) and landfilling.

Depending on the type of feedstock, geographical location, and socio-economic and political aspects there can be multiple scenarios drawn regarding the production and EoL management fate of bio-based plastics (**Column 2**), which may also depend on where the system boundaries are set. Moreover, the production of bio-based plastic resins may take place in a different region from where the feedstock is produced, having a shipment and trade involved. Here we adopted a simplified, more generic view of the entire system, acknowledging existing variability, yet placing emphasis on critical differences between bio-based plastics and their conventional (petrochemical-based) counterparts that they seek to replace. To navigate through our approach and paper, we developed a methodological overview of this work that is presented in Fig. 2. This methodological overview indicates the tools and approach to matrix development, limitations and potential of this work as described above.

For the sustainability matrix development, we did the following:

- To improve the interpretation of our sustainability matrix we used the symbols “>”, “<”, and “ = ” to indicate which of the two types of plastics (petrochemical-based vs bio-based), gives the greater (or equal) sustainability impact under the four sustainability domains (i.e., environmental, economic, social and technical).
- For clarity we also used the symbol “-” to indicate which of the two types of plastics gives the greater negative sustainability impact, and “+” to indicate which of the two plastic types gives the greater positive impact. In this way, we illustrated where information exists to favor the use of petrochemical-based plastics in terms of sustainability potential, and where information supports the use of bio-based plastics. It must be emphasized that this is a simplified representation, and is extremely sensitive to context and area-specific characteristics.
- Where evidence is inconclusive, or where there are debates around a specific impact we used the term “Controversial/Unclear”, whereas critical data gaps are highlighted as “Not specified”. The identification of these information gaps should direct future research needs. The term “Not applicable” was used when an impact was not relevant at the specific stage.

It must be noted that the interrelationships between the sustainability domains (i.e. environmental, economic, social and technical) and the impacts within them, are not considered in the context of this study.

3. Analysis of information collected from the literature

3.1. Raw material (feedstock) extraction

A considerable amount of resources, e.g., land, water, fertilizers and pesticides, and energy (Gironi and Piemonte, 2011) are commonly used for the cultivation and harvesting of agricultural crops used in the production of bio-based plastics (**Column 2**). In 2018, the land use associated with the production of bio-based plastics (**Column 2**) was estimated at 0.81 million hectares, and is expected to rise by 25% by 2023 (Bioplastics, 2019a). A global replacement of conventional plastics with bio-based alternatives (**Column 2**) could see an increase in the land-use change between 30 and 219 million hectares, i.e., around nine times the area of the United Kingdom (Putri, 2018). Land-use change refers to the conversion of natural landscape (e.g. forests) to other purposes (e.g. croplands) by human activities. This conversion can lead to adverse environmental impacts; it can affect climate via changes in surface physical properties (e.g. evapotranspiration) and carbon stock changes, it can contribute to biodiversity loss, and may cause soil erosion, eutrophication of ground and surface waters and carbon emissions (Hottle et al., 2013; Piemonte and Gironi, 2011, 2012; Rafiaani et al., 2018). Land use change may alter ecosystems, which in turn can bring wild species closer to humans. Increased interaction of wild animals with humans, can expose humans to new pathogens and increases the risk of zoonotic disease transmission (e.g. coronaviruses), as well as other infectious diseases (White and Razgour).

With regards to carbon emissions, Escobar et al (2018) reported that the replacement of 5% of global plastic consumption with bio-based plastics (**Column 2**) could lead to such an increase in the land use change that could take 22 years to offset the carbon emissions released (Escobar et al., 2018). The carbon emissions (CO_2eq) related to biomass feedstock production include: i) direct carbon emissions related to direct energy use via fuels (e.g., for machinery) and electricity (turbines, irrigation equipment, etc.) consumption on-site during the cultivation and harvesting (e.g., diesel, gasoline, propane, and natural gas combustion) and the emissions related to the use of fertilizers (e.g., nitrous oxide); and ii) indirect carbon emissions related to the off-site production of resources and electricity used in the field (e.g., seeds, fertilizers, pesticides, and fuels) (Iacovidou et al., 2017a). This means that the ‘carbon debt’ from land use change for the cultivation of 1st generation feedstock used in bio-based plastics production, could take more than 22 years to be paid back, termed as *carbon pay-back time* (Fargione et al., 2008). Spierling et al. (2018) stated that practitioners often consider the use of biomass as carbon-neutral (also termed as *biogenic carbon*, i.e. carbon contained in biomass that is accumulated during plant growth). This is because, growing biomass feedstocks removes CO_2 from the atmosphere and thus, compensates for the CO_2 released during biomass feedstock harvesting, processing and the related bio-based product’s EoL management (Spierling et al., 2018b). While this approach counts for the carbon benefits of using renewable feedstock, it ignores the carbon costs associated with the land-use change to replace the crops diverted to bioplastics (Piemonte and Gironi, 2012). In reality it could take more than 22 years to offset the carbon emissions related to bio-based plastics production.

The assumption of biogenic carbon neutrality is widely challenged on the basis of changes in soil carbon stock due to land use change and carbon storage capacities of long-rotation crops or wood products (Wiloso et al., 2016). As such, there is currently no consensus on how to account for temporary removals of carbon from, or additions to, the atmosphere in LCA and carbon footprint (CF) accounting. Chen et al. (2016) reflect this in their study where they conducted a LCA of petrochemical-based PET bottles with a range of bio-based PET bottles (**Column 2, Row 3**) comprising of 30%, 70% and 100% of lignocellulosic feedstock (Chen et al., 2016). The LCA employed encompassed feedstock extraction, component production and manufacture of 1 kg of resin to produce 100, 0.5 L capacity PET bottles, and assumed that biogenic carbon sequestration is achieved in bio-based derived PET bottles (Brandão et al., 2013). The results of this study revealed that the global warming potential of bio-based PET bottles ranged from 4.14 to 4.92 kg CO_2eq per kg of PET production; 21% lower than that from 100%

petrochemical-based plastic (i.e. 4.74–6.36 kg CO_2eq). In the alternative scenario, where biogenic carbon credits were not considered in the bio-based PET bottles production, it was revealed that bio-based PET bottles require more energy during production, and contribute to higher ecotoxicity impacts when compared to petrochemical-based plastics (Tucker and Johnson, 2004). Therefore, biogenic carbon accounting can be a significant determinant of the life-cycle GHG emissions of bio-based plastics (Tucker and Johnson, 2004).

Moreover, intensified agricultural production processes needed to support the replacement of conventional plastics with bio-based plastics can be associated with the use of considerable amounts of water and chemicals, in the form of pesticides and artificial fertilizers, as well as genetically modified organisms (GMOs) (Álvarez-Chávez et al., 2012; Alvarenga et al., 2013). Agricultural crops cultivation are responsible for the consumption of a significant amount of freshwater, especially in areas where irrigation is a prerequisite (Tsiropoulos et al., 2015). A study suggested that replacing conventional plastics with bio-based alternatives could lead to approximately 1.4 m^3/kg to 9.5 m^3/kg of water use, which corresponds to around 307 to 1652 billion m^3 global water demand per year (Putri, 2018). This contributes to around 13%–60% of the total global agricultural water demand (for comparison agricultural water demand accounts for roughly 70% of total global water demand) (The United Nations, 2019). In areas where rainwater is sufficient, water consumption aspects could be regarded (at least for the time being) negligible. Nonetheless, the water intensity of feedstock cultivation for bio-based plastics production (e.g. sugarcane) (Tsiropoulos et al., 2014), is often higher than the water consumption for petrochemical-based plastics production (Alvarenga et al., 2013), which may result in water security issues depending on regional/ local water stress. Water security could also be impacted through nutrient loading (i.e., contamination of water by certain pollutants) that influences the availability and quality of surface water and groundwater, impacting directly on people's livelihoods (Rafiaani et al., 2018).

Fertilisers and pesticides are applied to increase agricultural production and reduce the economic costs from plant diseases, pest control and weeds. Nonetheless, fertiliser use in feedstock growing practices, can lead to higher acidification and eutrophication impacts, whilst the artificial fertiliser production itself is also 'costly' in terms of energy use and resource depletion (Cheng et al., 2020). Fertiliser use can disturb the nitrogen and phosphorus cycles through surface run-off and leaching, leading to water pollution, acidification, eutrophication and habitat degradation in the surrounding terrestrial and aquatic ecosystems and their services[2] (Alvarenga et al., 2013; Liu and Xie, 2019; Brentrup et al., 2004), leading to long-term negative environmental and human health impacts (Gasparatos et al., 2011). Tsiropoulos et al (2015) showed that the eutrophication caused by sugarcane cultivation towards bio-based plastics production can be many times higher compared to petrochemical derivatives (Tsiropoulos et al., 2015), which is in line to the findings of Hottle at al. (2017) (Hottle et al., 2013). The production of nitrous oxides (NO_x) and ammonia (NH_3), due to volatilisation occuring during and after the application of urea and ammonium-containing fertilizers, may lead to an increase in the acidification potential, which can be higher than that associated with petrochemical-based plastics production (Brentrup et al., 2004). Improving the sustainability of fertiliser production is therefore one strategy that could improve the sustainability credentials of bio-based plastics. This topic is now attracting a lot of scientific interest, and methods such as reverse flotation separation to produce high-grade potassium (Huang et al., 2020a) and phosphorous based fertilisers (Huang et al., 2020b) at low temperatures appear to be promising.

Soil erosion and degradation associated with deforestation and intensive agriculture related to increased biomass feedstock cultivation for bio-based plastics production, can lower the quality of land resources and agricultural productivity, thereby affecting food security (Rafiaani et al., 2018). These impacts, alongside the potential exposure of farmers and surrounding communities to the pollution caused by the chemical fertilisers and pesticides used in crops production, can result in negative impacts on human health and income. The severity of environmental and human health impacts is highly dependent on the socio-economic context of the country, where biomass is being produced and harvested. For example, there are well documented intersections between the impacts of agrochemicals and human rights issues, such as the inadequate protection of agricultural workers or child labour, that are particularly pertinent when considering vulnerable populations such as women of childbearing age, or children (UNHRC, 2018).

On the economic domain, the cultivation of feedstock for bio-based plastic production can be associated with considerable costs. These cost can be related to: land clearing (either by outsourcing the services, or hiring specialised machinery for such purposes); purchase or renting of machinery and all other equipment needed (e.g. tractors for ploughing, irrigation technologies, turbines); fuel for machineries operation and electricity consumption; planting (including the price of seeds and stems, depending on the type of feedstock); pesticides and fertilisers; and harvesting and transportation to processing facilities. The aforementioned costs may vary widely depending on the country, landscape, type of land, type of feedstock and whether is operated by small- or large-scale farmer. It must be noted, however, that as the expansion of agricultural land occurs mostly in developing countries (e.g., Brazil, India (Alvarenga et al., 2013; Tsiropoulos et al., 2015), Thailand (Petchprayul et al., 2012), Indonesia (Restianti and Gheewala, 2012)), these costs can be particularly important for small scale farmers. It may lead to additional trade-offs, such as competition for land required for food production and other services required for human well-being (Álvarez-Chávez et al., 2012). The competition between bio-based plastics feedstock and food, it can affect food availability and cost, and thus food access; leading to implications for local food security (Storz and Vorlop, 2013; Escobar et al., 2018; Gasparatos et al., 2011). Food insecurity can escalate concerns on global food crisis, which in turn can result in conflicts and social unrest especially in developing countries (Álvarez-Chávez et al., 2012). Food insecurity may also result in food price fluctuations and implications on trade, which can have a direct impact on the costs of agriculture, livestock and forestry sectors (Escobar et al., 2018).

On the up-side, forest clearing for feedstock cultivation for bio-based plastics (**Column 2**) production can create more jobs for the rural communities, leading to the expansion of agricultural economies and provision of substantial economic and social benefits (Rafiaani et al., 2018). It can create new job opportunities, reduce poverty, improve the livelihoods of people living in impoverished communities, lead to a migration decline, and contribute to the reinforcement of local community (Spierling et al., 2018b; Restianti and Gheewala, 2012). In turn, this could increase the income of farmers living in rural communities; with better income these people will gain access to food and other goods. However, these benefits can be gained when reliable legal frameworks and

[2] The direct and indirect benefits that human obtain from nature that fall into four broad categories: provisioning services (e.g. food, fuels); regulating services (e.g. climate regulation, pollination, disease control); cultural services (e.g. recreational, spiritual, aesthetic); and supporting services (e.g. nutrient cycling, soil formation).

contracts are implemented (Spierling et al., 2018b), whereas they can be less important in areas where food access may depend on local food production than on household income (Rafiaani et al., 2018; Herrmann et al., 2018).

On the technical side, intensive agriculture can be accompanied by an intensification of production methods, i.e. expansion of irrigation and adoption of modern methods of agriculture, contributing to technical and economic sustainability as crop losses are reduced. With higher income, farmers would be able to invest in technologies that can help them expand their production base, which could increase their productivity. In the long-term however, this may result in lower profit margins per unit of output, which in turn will lead to intensification of their activities as they will aim to produce a bigger amount of feedstock. Higher feedstock demand will require more cropland and higher cropping intensities impacting on the environmental and social sustainability (Álvarez-Chávez et al., 2012; Collaborative and S.B, 2009).

3.2. Processing/manufacture

There are several types of 1st generation feedstocks that can be used in bio-based plastics production, namely, sugar cane, corn, maize, wheat, cassava, etc. (Spierling et al., 2018b). Each type of feedstock has its own characteristics, and as such different processes are involved at their processing stage. For instance, not all feedstocks require pre-treatment, e.g. corn does not require pre-treatment (Ögmundarson et al., 2020a), while sugarcane needs to be crushed (Tsiropoulos et al., 2014). Biorefinery processes differ according to the composition of the processed biomass. For instance, feedstocks such as sugarcane, corn and cassava can undergo a microbial conversion into glucose, which in turn is (glucose) converted into various monomers (intermediaries) that are suitable for polymer production such as lactic acid, succinic acid, butanediol, ethanol etc. (Chen and Patel, 2012).

Polylactic acid (PLA) (**Column 2, Row 2**) currently the most popular and commonly used resin in bio-based food plastic packaging production is obtained from the bacterial fermentation of starch into glucose and further condensation of lactic acid (Ubeda et al., 2019), whereas bio-PE and bio-PET (**Column 2, Row 3**) are obtained from the bacterial fermentation of sugarcane into glucose and further dehydration of ethanol (Chen and Patel, 2012). Ethanol is dehydrated to ethylene and is either polymerised to polyethylene (for bio-PE production), or is oxidised to ethylene oxide and then hydrolysed to bio-based mono-ethylene glycol (bio-MEG), the bio-based component of bio-PET (Tsiropoulos et al., 2015). Polybutylene succinate (PBS) (**Column 2, Row 2**) another bio-based plastic is produced from sugarcane fermentation into glucose and further poly-condensation of succinic acid (SA) and 1,4-butanediol obtained from renewable resources (Petchprayul et al., 2012; Succinity and Biobased Polyb).

The biorefinery and polymerisation processes are generally associated with high energy requirements (although there are variations depending on feedstock type) which can be lower, or higher than the energy required to produce petrochemical-based resins (**Column 3**), leading to controversies in regards to the impact of the bio-based plastics production on carbon emissions and associated GWP (Ögmundarson et al., 2020a; Changwichan et al., 2018). For instance, corn grain ethanol production can be more energy intensive than petrochemical plastic resin production (Hill et al., 2006). Moreover, the production of bio-HDPE is reported to lead to approximately 140% savings in CO_2eq compared to the petrochemical-derived HDPE (Tsiropoulos et al., 2015), whereas bio-PBS production can lead to comparable CO_2eq as its petrochemical counterpart (Petchprayul et al., 2012). Chen et al (2016) reported that woody feedstocks are highly lignocellulosic and resistant to degradation (Khanna, 2008), and as such, their conversion to a bio-based polymer resin requires an integrated biorefining processes that involves the pre-treatment, enzymatic hydrolysis, fermentation and further processing to iso-butanol (i.e., the starting monomer of bio-based plastic). This conversion process requires more energy than conventional fossil oil production, and therefore produces more GHG emissions and higher ecotoxicity impacts when compared to fossil oil plastics (Chen et al., 2016). It should also be noted that polymerisation can be more energy intensive than biorefinery depending on the feedstock type and polymer production, and vice versa (Hottle et al., 2013; Chen and Patel, 2012). For example, in PLA production polymerisation is more energy intensive than biorefinery, whereas in PBS production biorefinery is the most energy intensive step (Petchprayul et al., 2012). Spierling et al. (2018a,b) suggested that if bio-based alternatives (**Column 2**), such as starch-based, PLA, PHA/PHB and drop-in bioplastics (i.e. bio-based plastics with identical chemical structure with their conventional counterparts such as bio-PET, bio-PP, etc.) could replace around 66% of their petrochemical counterparts (**Column 3, Row 3**) they could save around 241 to 316 million CO_2-eq annually (Spierling et al., 2018b). However, the authors clarify that these energy savings are associated with variations on the energy mix that includes energy from renewable resources (Spierling et al., 2018b; Tsiropoulos et al., 2015), or by-products produced during the pre-treatment and biorefinery processes (e.g. bagasse, sludge, etc.). Lack of information in regard to the energy intensity of the biorefinery/polymerisation process can distort transparency in regard to actual carbon emissions associated with the bio-based plastics production, as opposed to their conventional counterparts.

Apart from their contribution to GWP and fuel depletion (energy), biorefinery and polymerisation processes can also produce a range of hazardous air pollutants. Carbon monoxide (CO), sulphur dioxide (SO_2) and volatile organic compounds (VOCs) are emitted from the coal or natural gas boilers used in biorefinery processes, contributing to acidification and toxicity potential (Restianti and Gheewala, 2012; Eberle et al., 2017). During the biorefinery and polymerisation processes, inputs such as neutralizing agents (e.g. phosphate, and lime (a calcium hydroxide solution)), and other chemicals are added to stabilise and ensure the efficiency of the processes, which can impact on the environmental and economic viability of the bio-based plastics production (Ögmundarson et al., 2020a). For example, during the biorefinery process for the production of PLA, lime (calcium hydroxide solution) must be added to neutralize the lactic acid produced by microbes and control the pH of the fermentation process to retain optimal operational conditions. A calcium-based salt (calcium lactide) is then formed, which is acidified to release lactic acid needed for PLA production, generating also by-products (e.g. gypsum (calcium sulphate) that could be used in other industrial processes or soil conditioner, or disposed as waste (Jem and Tan, 2020; Vink and Davies, 2015). PLA and TPS, which are both manufactured using corn, contribute higher to the acidification potential than petrochemical-based plastics, as a result of the effluent wastewater generated in starch production, and the use of plasticizers at the polymerisation stage (Hottle et al., 2013).

The use of chemicals at the polymerisation stage of bio-based polymer resins (e.g. PLA with enzymatic methods) can impact on the health and safety of workers (Álvarez-Chávez et al., 2012). Workers can be exposed on toxic substances and safety hazards during these stages, while there is also a risk of fire hazard during the biorefinery stage (Clark and Hardy, 2004). Furthermore, when bio-based polymer resins are transformed from pellets to final products via injection or blow moulding, thermoforming or film extrusion and variations of these due to the different techniques used, a wide range of chemicals known as additives are used (Ubeda et al., 2019; Hahladakis et al., 2018a). This is due to the varying properties of the polymers and the range of formation technologies used for the different types of bio-based biodegradable (**Column 2, Row 2**) and non-biodegradable (**Column 2, Row 3**) plastics, as well as the product shapes, sizes, lifetime, and functions (Hottle et al., 2013). For example, to deal with PLA's brittleness, low resistance to oxygen permeation, and poor heat stability, chemicals such as modifiers or plasticizers acetyl (tributyl citrate) (ATBC) or polyethylene glycol (PEG) may be intentionally added (Arrieta et al., 2014). Additionally, to improve the thermal stability of PLA, antioxidants such as butylated hydroxytoluene (BHT) or fillers may be intentionally added during manufacture (Ortiz-Vazquez et al., 2011). The use of BHT is regulated in many jurisdictions such as the United States or the European Union and it has been listed as a potential endocrine disrupter in a United Nations Environment Programme report, signifying potential social concerns, as due to its volatile nature it can be an occupational hazard during the manufacture process (IPCP, 2020).

Nanoparticles (NPs) are emerging contaminants that have been used as polymer additives either to enhance biopolymer performance; cellulose nanostructures have been widely used as bio-based fillers due to their biocompatibility, abundance, barrier properties and low cost (Fortunati et al., 2014; Maisanaba et al., 2014), or as antimicrobials (e.g. silver, zinc oxide or titanium dioxide NPs) (Martínez-Bueno et al., 2017), mineral clays or chitosan (a nanofiber membrane) can be incorporated within the PLA matrix, to give it additional properties that improve its functionality as a packaging material (Llana-Ruíz-Cabello et al., 2017). However, the toxicity of these NPs is often less well understood. Natural extracts or essential oils have also been used for their antioxidant or antimicrobial properties in active packaging including bio-based plastics (Llana-Ruíz-Cabello et al., 2017). In addition to intentionally added substances (IAS), non-intentionally added substances (NIAS) may also be present in the polymeric material (Canellas et al., 2015), most of which are related to thereafter stages.

On the economic domain, the current pricing level of bio-based plastics is higher than that of conventional plastics due to the relatively low oil prices compared to feedstock extraction and the cost of investment in bioplastics (Bioplastics, 2020). However, the price of bio-based plastics has presented a downward trend over the last decade as their volume in the market has increased and the production processes have improved (Bioplastics, 2020). The biorefinery stage incurs the largest part of the operational cost of bio-based plastics (**Column 2**) production, which is reported to be about two to three times higher than that of petrochemical-based plastics (Changwichan et al., 2018). The high production cost of bio-based plastics (**Column 2**) is attributed to feedstock acquisition (Brown, 2015), and the utilities costs associated with the processing (Changwichan et al., 2018). In regards to equipment costs, the processing technologies that are currently used for the production of biofuels can be used in the production of bio-based plastics (**Column 2**), however, the steps involved and the operating conditions will need to be adjusted depending on the feedstock used, microbes, and media, leading to costs variances. This is to ensure that processing meets the specifications of each bio-polymer, and is not considered to be a major challenge (Bioplastics, 2019b). The biggest challenge is with regards to scaling up and upgrading existing infrastructure to meet future demand in the amount of bio-based plastics produced. This is anticipated to bring up the investment costs, but it can potentially create new jobs. An increased availability of skilled positions that may provide long-term contracts with better working conditions and a higher wage, could make bio-based plastics production an attractive employment opportunity available at all levels and for both women and men (Duarte et al., 2014).

On the technical side of things, each biorefinery refines and converts its corresponding biological raw materials into a multitude of valuable products. The technologies used in biorefineries are important at improving the efficiency yield of different products and can result in economic and environmental benefits. For instance, a new fermentation technology used in PLA production that can significantly reduce the use of calcium hydroxide and sulfuric acid, can lower the cost of the process and occupational hazards and emissions, whilst leading to significantly lower quantities of gypsum that require processing (Hill et al., 2006; Brown, 2015). Process optimisation in biorefineries could justify the large investment costs, but currently further development of thermal, chemical and mechanical processes, such as gasification (syngas) and liquefaction of biomass, are still trialled. The real challenge with the biorefineries is that those constructed in developing countries often do not have environmental protection technologies included in their designs, such as baghouses, flue gas desulfurization (FGD), and other systems that can reduce PM, SO_2, and NOx emissions, respectively (Eberle et al., 2017). This contributes to environmental pollution and health related impacts, and is an issue that needs to be addressed to ensure better air quality and reduced pollution.

3.3. Use (and disposal)

Impacts associated with the use of bio-based plastics are closely linked to their manufacture and design. The IAS and NIAS have the potential, and some have been shown, to migrate from bio-based packaging into food (Canellas et al., 2015). Migration depends on many factors such as food composition (acidity, fat or alcohol content) or temperature as previously mentioned, BHT gives rise to concerns due to its putative endocrine disrupting properties, specifically on the thyroid (Maisanaba et al., 2014). As a result the use of this packaging signifies potential social concerns, as BHT can migrate from PLA to the food during the use phase presenting a potential risk to human health (IPCP, 2020). The migration of chemical substances from food contact materials into food has been shown to be a neglected route of chemical exposure (Muncke et al., 2020). The assessment of risks deriving from contaminants migrating into food from packaging material is presently hindered by the lack of toxicological data (Muncke et al., 2017).

Migration experiments comparing bio-based and fossil-based plastic packaging are extremely rare. To our knowledge, there is only one study that examined the migration of IAS and NIAS from an acrylic adhesive used in food contact applications through polyethylene (PET), polyethylene terephthalate (PET), polypropylene (PP), PLA and Ecovio F2223® a blend of biodegradable polyester with PLA (Canellas et al., 2015). In this study, they found that the lowest migration was observed when the compounds passed through PLA, demonstrating its functional barrier properties to these compounds. In contrast, PE showed the worst barrier properties. Nonetheless, due to their biodegradability, there are concerns about the lack of thermal stability and potential migration of degradation products such as, lactic acid, lactoyl-lactic acid, lactide and oligomers, especially in the case of PLA (Mutsuga et al., 2008; Dopico-García et al., 2012). Current guidelines for migration testing do not consider the potential aging of biodegradable polymers (Dopico-García et al., 2012). Functional barriers are components of food contact materials used to effectively reduce or inhibit the migration of contaminants that are used in multilayer structure. Depending on their composition, functional barriers may present sustainability trade-offs in terms of its recyclability or biodegradability potential.

As public awareness and acceptance of bio-based plastic packaging are growing, so have considerations surrounding their sustainability in food packaging applications. According to a Eurobarometer survey, nearly 75% of consumers in Europe support products that use low amounts of natural resources and contribute less to GHG emissions (Eurobarometer, 2014). However, challenges related to preference, choice and use of bio-based plastic packaging may remain as their disposal and management can be quite problematic (Bioplastics, 2020). The disposal of bio-based plastic plastic packaging waste (**Column 2**) is closely linked to citizen's behaviour; a main denominator of environmental, economic and social impacts (Piemonte and Gironi, 2012). Disposal of bio-based plastic packaging waste requires an understanding of the distinction between biodegradable (**Row 2, Column 2**) and non-biodegradable bio-based plastics (**Row 3, Column 2**). Currently there is no separate collection of bio-based plastics (biodegradable or not), and the cost of introducing one can vary from an area to another, while it can be alsovery high, thus justified only when sufficiently large quantities of bio-based plastics (**Column 2**) are placed on the market (Soroudi and Jakubowicz, 2013). However, some types of bio-based plastics (**Column 2**) can be collected and managed in the existing collection and management infrastructure, however, confusion and lack of guidance presents several challenges to the waste management industry and the economy as a whole. This is due to the public misconception that all bio-based plastics (**Column 2**) are biodegradable (**Row 2**).

The misconception that all bio-based plastics are biodegradable can result to plastic packaging waste ending up and contaminating the organic waste streams (i.e. food and green waste), while to some extent it can undermine efforts to avoid littering and curbing plastic pollution. Consumers often assume that plastics that are biodegradable can break down in the natural environment making littering 'somewhat' acceptable (Rujnić-Sokele and Pilipović, 2017; Kershaw et al., 2015). In reality the degradation rate of bio-based biodegradable plastic packaging waste (**Row 2, Column 2**) in the natural environment can vary considerably and might never be fully achieved (Rujnić-Sokele and Pilipović, 2017). Moreover, Tucker and Johnson (2004) found that the biodegradation of some kind of biodegradable polyesters in the natural environment can release cytotoxic or phototoxic substances that can pollute the environment and create risks to human health and ecosystems.

An additional challenge related to bio-based plastic packaging waste (**Column 2**) disposal is due to the labelling system currently used. Bio-based plastics are generally labelled with resin identification number 7 ("other plastic"), which to many people's mind is the non-recyclable plastic category. This can impact on the recyclability/compostability potential of bio-based plastic packaging waste (Changwichan et al., 2018; Álvarez-Chávez et al., 2012), and undermine efforts to promote resource efficiency and recovery of value. This can shift environmental burdens to new points in the value chain rather than reducing the overall life cycle impacts (Iacovidou and Gerassimidou, 2018; Hahladakis et al., 2018b), generating important trade-offs in regards to their imminent use (Álvarez-Chávez et al., 2012). An apt disposal of bio-based plastic packaging waste needs to be aligned with efforts of informing consumers on the type and EoL management potential of the several types of bio-based plastic packaging placed on the market (**Column 2**). For the development of a sustainable bio-based economy, it is necessary to establish a reliable and trustworthy certification approach on national, European, or even at a global level (Majer et al., 2018). Eco-labels that are designed to communicate the sustainability credentials of bio-based products to encourage the behavioural change of producers and consumers towards long-term sustainability can be extremely beneficial (Ogunola et al., 2018). However, it is also acknowledged that such branding is widening the gap between perception and fact, guided by misinformation (Zielinski and Botero, 2019).

3.4. EoL management

The EoL management of bio-based plastic packaging waste (**Column 2**) involves landfilling, industrial composting, anaerobic digestion, incineration with or without energy recovery, mechanical biological treatment for the production of refuse derived fuel (RDF), or solid recovery fuel (SRF), e.g. used in cement kilns, as well as mechanical or chemical reprocessing (Maga et al., 2019; Rossi et al., 2015). The choice of the EoL management option used often depends on the context (i.e., developed vs developing country and existing infrastructure), the source of bio-based plastic waste (e.g. consumer, commercial, construction), as well as on whether the bio-based plastics are biodegradable (**Column 2, Row 2)** or non-biodegradable (**Column 2, Row 3**).

Designing of a sustainability assessement scheme for bio-based plastic packaging necessitates an adequate legislative framework including sustainability certifications, standards and labels that ensures a level playing field between bio-based and conventional plastics (Falcone and Imbert, 2019). Regulatory measures for assessing the sustainability performance of bio-based packaging products should include not only environmental but also socio-economic criteria, and should establish specific thresholds prior to increasing their market acceptance (Wurster and Ladu, 2020). Wurster and Ladu (2020) reported a list of criteria that need to be included in ecolabels of bio-based plastic food packaging products: bio-based content; CO_2eq emissions; toxicity; EoL options; fitness for use related to product functionality and performance; corporate social responsibility related to human and labour rights; human health and safety; biomass utilization efficiency related to the amount of feedstock versus the biomass content of product; and lifecycle costs (Wurster and Ladu, 2020).

The need to consider socio-economic aspects when assessing the performance of bio-based plastics has been also reported by D'Adamo et al. (2020). In their study, using a socio-economic indicator (SEI) they carried out an integrated analytic hierarchy process-multicriteria decision analysis with which they assessed varying EoL management options for PLA film used in food packaging applications, namely, mechanical and chemical recycling, anaerobic digestion, composting, reuse, energy recovery and landfilling (D'Adamo et al., 2020). They found that mechanical and chemical recycling preformend better compared to the rest of the EoL management option epseically with regards to socio-economic preformance. For the analysis they used criteria relevant to five stakeholder catgories: i) workers, ii) consumers, iii) general society, iv) the local community and v) value chain actors. They suggested that the value chain actors (e.g. seed suppliers, farmers, traders, processors, transporters, wholesalers, and retailers) was the most influential category on the EoL management of bio-based plastic packaging waste (D'Adamo et al., 2020).

Notwithstanding the above findings, according to the waste hierarchy, introduced in the European Waste Framework Directive (2006/12/EC), bio-based biodegradable plastic packaging waste (**Column 2, Row 2**) could be best managed via composting and anaerobic digestion (AD) processes (although some types can also be mechanically reprocessed, e.g. PLA), whereas for bio-based non-biodegradable plastics (**Column 2, Row 3**) the mechanical reprocessing option is considered the most preferable option, following prevention and reuse (Changwichan et al., 2018; Piemonte and Gironi, 2012; Maga et al., 2019; Rossi et al., 2015). Chemical reprocessing, in spite of its merits, is not yet considered a viable option owing to the fact that currently, there is no large scale process in operation (Soroudi and Jakubowicz, 2013; Faisal et al., 2006).

Incineration with energy recovery, a process known as energy from waste (EfW), can also be used for the management of bio-based plastic packaging waste (**Column 2**). EfW an option with little merit as it does not promote the recovery of the material *per se*, and as a result it often does not compare well with recycling processes in regards to GHG emissions and energy use. Nonetheless, EfW recovers the energy content of the material and can be applied easily without adjustments in the combustion systems (Rujnić-Sokele and Pilipović, 2017); thus, a preferable option to incineration without energy recovery and disposal to landfill. Sending any type of bio-based plastic waste to landfill can result to deleterious effects on the environment, and human health, due to greenhouse gases emissions, chemicals leachate, and air, soil and water pollution via microplastics formation. Preservation of natural resources is another aspect that necessitates landfill mining in view of the circular economy.

Mechanical reprocessing, composting (incl. some reference to AD), and EfW are the three EoL management options that have been researched in the literature.

3.4.1. Mechanical recycling

In terms of environmental performance, bio-based plastics (**Column 2**) that can undergo mechanical reprocessing were ranked in the following order when compared with their petrochemical counterparts (**Column 3**): PLA > PP > PBS > PHAs. The mechanical recycling of PLA can reduce the consumption of raw materials; hence it lowers demand for arable land and contributes less to carbon emissions and energy consumption (Maga et al., 2019; Beltrán et al., 2019). This is in agreement with D'Adamo et al (2020), who reported that the best EoL management option for PLA-based film for food packaging is mechanical recycling. Nonetheless, evidence that mechanical recycling of bio-based biodegradable plastics (**Column 2, Row 2**) can have a net sustainability benefit over their conventional counterparts is sparse (Spierling et al., 2018b; Piemonte and Gironi, 2012). This is in addition to the high investment required for the installing the appropriate collection and sorting infrastructure, and the small volumes of bio-based plastics (**Column 2**) flowing in the economy (Spierling et al., 2018a). Investments on the right labelling, collection, and sorting technologies and infrastructure are needed since bio-based plastics (**Column 2**) have poorer technical properties than conventional plastics (**Column 3, Row 3**) leading to their higher sensitivity to processing cycles (Spierling et al., 2018a).

In terms of technical performance, the polymeric structure of bio-based biodegradable plastic packaging waste (**Column 2**, **Row 2**) was found to be affected by the thermochemical degradation during the mechanical reprocessing stage, leading to alteration of polymer properties (Spierling et al., 2018a; Soroudi and Jakubowicz, 2013). Potential solutions to this shortcoming are focused on the use of suitable additives and compatibilizers to deal with immiscibility and incompatibility challenges (Hahladakis et al., 2018a; Żenkiewicz and Kurcok, 2008). This has led to the use of maleic anhydride as a compatibilizer, and bio-based polyols castor oil and ricinoleic acid as precursors for the preparation of polyurethane dispersions (PUDs) for the preparation of block copolymers via reactive processing, even though various other combinations are also possible. Several groups have reported improved adhesion, morphology and mechanical properties in systems prepared by this approach (Vidéki et al., 2005, 2007). However, these solutions may have a knock-on effect on the suitability of recycled bio-based plastics for use as a food-contact material due to chemicals migration. However, due to the lack of information on this aspect we cannot draw any sound conclusions.

Repeated processing cycles were found to degrade some of PLA's properties, i.e. reduction of tensile strength, thermal stability, viscosity, cold crystallization temperature and melting point, whereas PHA was found to be more resistant with some losses/degradation observed on its molecular weight and mechanical properties, respectively (Soroudi and Jakubowicz, 2013; Beltrán et al., 2019). Blending conventional (**Column 3**) with bio-based polymers (**Column 2**) is regarded as a potential solution from the perspective of resource preservation and property improvement, yet it can considerably degrade the quality of the successive material (Soroudi and Jakubowicz, 2013). For example, blends of PLA and PS are used in packaging industry producing a cheaper product compared to pure PLA (Soroudi and Jakubowicz, 2013). However, after four cycles of processing the stress and strain at break of the blend significantly decreases, while after each cycle the viscosity of the blend is reduced by 15–30% (Hamad et al., 2011).

Existing separation methods add to this challenge, as they are not capable of separating efficiently conventional plastics (**Column 3, Row 3**) from bio-based resin types (except of bio-PE, bio-PET, and bio-PP) (**Column 2**) (Soroudi and Jakubowicz, 2013) with the latter becoming a source of contamination and quality degradation. For instance, the contamination of PET bottles by the bottles composed of PLA is a major concern for the food packaging industry. NIR technology can only recover 93% of PLA bottles from the PET recycling stream, with the potentially remaining amount (even as low as >0.1%) destroying an otherwise perfectly recyclable batch (Soroudi and Jakubowicz, 2013). This presents an important economic challenge for reprocessors, who do not want to risk the quality of their secondary material, as this could result in lower profit margins for their business. As a result, investments in upgrading sorting equipment, such as NIR sensors are currently being sought after by waste management companies in order to sort PLA from the high value streams. This can drive up the capital costs of sorting processes, but in the long-term can secure a higher revenue from the selling of clean plastic waste to recyclers (Soroudi and Jakubowicz, 2013).

The drop-in plastic packaging waste (e.g. bio-PET, bio-PE, bio-PP) (**Column 2, Row 3**) that have identical properties to their conventional counterparts, are currently the only types of bio-based plastics that are typically considered suitable for mechanical recycling. Existing sorting facilities can theoretically be used for their sorting and management, along with their petrochemical counterparts (e.g. PET, PP, HDPE) (**Column 3, Row 3**); hence these alternatives can theoretically be effectively managed in the current recycling system.

3.4.2. Composting (incl. some reference to AD)

Not all biodegradable plastic packaging waste (**Row 2**) can degrade in the natural environment, and some may not even be compostable under the established and commonly used methods of composting. Typically biodegradable plastic waste (**Row 2**) require longer periods of time to degrade compared to other organic wastes (van den Oever, 2017), and certain conditions must be followed for their complete degradation (Emadian et al., 2017). These conditions may vary considerably depending on the chemical structure of the polymer, environment, and type of degradation (Iacovidou and Gerassimidou, 2018). Whereas bio-based biodegradable plastics (**Row 2, Column 2**) contribute to the preservation of natural resources and abatement of GHG emissions, composting of biodegradable plastic packaging waste is considered a less effective EoL management option with regards to GHG reduction in comparison to mechanical recycling. For example, Piemonte and Gironi (2012) found that composting of PLA bottles can increase GHG up to 38% compared to recycling (**Column 2, Row 2**). This brings back the debatable issue of biogenic carbon (see Section 4.1) and how this is properly accounted in the life cycle assessment tools used. The use of bio-based plastics (**Column 2**) is often justified by the fact that they biodegrade faster than fossil-based plastics (**Column 3**), but the fact that the demand for the resources of biomass production could expand uses of land, fossil fuels, chemical inputs, and water should be considered (Luzi et al., 2019).

Bio-based biodegradable plastic packaging waste (**Column 2, Row 2**) differ on their biodegradability rate and potential; with some types be completely degraded by microorganisms and others decomposed into small particles (i.e. microplastics) (Hahladakis and Iacovidou, 2018). For example, PBAT, PHA, PBS and starch derived polymers are suited for degradation in home composting environments at temperatures of around 35 °C and thus a range of controlled and uncontrolled environments may be suitable for their management (Narancic et al., 2018), whereas PCL can only biodegrade under anaerobic conditions at 20–45 °C using mesophilic microorganisms (Ruggero et al., 2019). PLA can take 45–60 days to degrade at a thermophilic temperature range of 50–60 °C (Tokiwa and Calabia, 2006), and therefore it is not suitable for home composting, open window composting, or mesophilic anaerobic digestion. As a result, EoL management options for the commercially available PLA are limited to thermophilic digestion and industrial in-vessel composting.

Rossi et al (2015) reported that PLA contains nutrients in trace amounts, and this is an issue for two reasons: 1) neither the aerobic and anaerobic decomposition can be carried out without nutrients for the microorganisms to function properly; and 2) a compost or digestate output would not be rich in nutrients that can replace N–P–K fertilisers (Rossi et al., 2015). In addition, the fibrous or porous texture of the by-product generated during the composting or digestion process cannot provide any soil structure improvement, nutrient retention, erosion and runoff reduction, or herbicide and water requirements reduction (Rossi et al., 2015). This highlights that composting, or AD of bio-based biodegradable plastic packaging waste only makes sense when mixed with organic wastes, yet the ratio of bio-based biodegradable plastics (**Column 2, Row 2**): organic wastes needed for ensuring minimum disturbance in the composting and/or AD processes remains presently unclear.

With regards to costs, the advantage of bio-based biodegradable plastic packaging waste depends on whether existing infrastructure could be used for their management without any major adjustments. At present it is not feasible to manage the majority of bio-based biodegradable plastic packaging waste in composting (or even AD) facilities because of they cannot be fully degraded, thus posing a risk to the success of the management process and marketability of its outputs. Meanwhile, the lack of appropriate routes for the management of bio-based biodegradable plastic waste, increases the costs at composting and AD facilities as operators strive to remove these materials, now regarded as contaminants, and are then burned or landfilled.

Improving the properties of bio-based biodegradable plastics to improve their biodegradability at the manufacturing stage, is possible. However, chemical additives that could give properties that are important to promote biodegradation at the end-of-life may present challenges during other lifecycle stages, such as the storage and use. For example, the ester linkages in PLA are sensitive to both enzymatic and chemical hydrolysis and may affect its thermal stability during storage (Ortiz-Vazquez et al., 2011). BHT or fillers can be intentionally added during manufacture to protect the polymer at the storage stage, yet this could affect the sustainability of the use and end-of-life phases.

3.4.3. Energy-from-waste (EfW)

According to the European Commission (EC) policy recommendation, waste-to-energy (WtE) processes can maximise the circular economy's contribution to decarbonisation only by respecting the waste hierarchy making co-combustion processes energy-efficient techniques widely adopted in Europe (European Commission, 2017). Endres and Siebert-Raths (2011) measured the calorific value of bio-based polymers (**Column 2**), which is an economic attribute (WRAP, 2012), and compared them with the calorific value of conventional plastics (**Column 3, Row 3**). Results showed that the heating value of bio-based polymers (**Column 2**) depends on their stoichiometric composition and not on the source of raw materials. As a result, drop-in bioplastics have an equal heating value to their conventional counterparts due to same elementary composition. In addition, the calorific value of biodegradable bio-based plastics (**Column 2, Row 2**), such as PLA, starch-based and PHAs fluctuates between 19 and 24 MJ/kg, which is lower than the calorific value of the prevalent conventional plastics (**Column 3, Row 3**) in packaging, such as PE, PP and PS (40–45 MJ/kg) but similar with conventional polymers, such as PET and PVC (18–22 MJ/kg) (Endres and Siebert-Raths, 2011).

From the perspective of gas emissions emerging from combustion, which is an environmental attribute (WRAP, 2012), the thermal behaviour of bio-based plastics (**Column 2**) is similar with that of petrochemical-based plastics (**Column 3, Row 3**) (Endres and Siebert-Raths, 2011). As a result, no modification or adjustment of the existing combustion facilities is required making the co-combustion of bio-based plastic packaging waste (**Column 2**) and petrochemical-based plastic packaging waste (**Column 3, Row 3**) feasible (Endres and Siebert-Raths, 2011). However, WtE is a recommended process only if bio-based plastics (**Column 2**) can no longer be recycled. It is a feasible EoL option from the technical point of view, but special attention should pay on the risk of waste-to-energy to sabotage recycling.

4. Sustainability matrix: critical aspects

Following the evidence presented in Section 3, we developed a sustainability matrix (Fig. 3) to depict current knowledge on the challenges and trade-offs associated with the replacement of conventional (petrochemical-based) plastic with bio-based alternatives in the food packaging sector (**Column 2**). The sustainability matrix presents the crude life cycle stages explained in Section 2.2, analysed based on the four sustainability domains, i.e., environmental, economic, social and technical.

In our analysis, there is no distinction between bio-based biodegradable plastics (**Column 2, Row 2**) and bio-based non-biodegradable plastics (**Column 2, Row 3**). While specificity and granularity is tremendously important to assessing the sustainability potential of bio-based plastic materials placed on the market, and their lifecycle impact, there is also value in capturing key aspects that ought to be evaluated when considering a specific material or application. Moreover, the purpose of the sustainability matrix is to highlight issues relevant to high-level policy and decision-making processes. Despite the existence of a wide variety of certification frameworks, criteria, indicators and applicable standards in the food sector towards the use of bio-based products, our matrix reveals that there are several gaps that need to be addressed. These gaps are related to: existing criteria sets; practical implementation of criteria in certification processes; the legislative framework; end-of-life processes; as well as necessary standardisation activities (Majer et al., 2018).

Fig. 3 shows that there are several metrics that need future research to ascertain the potential superiority of bio-based plastics against conventional plastics in terms of sustainability performance in the food packaging sector. The metrics outlined under each domain represent the synthetic analysis of the reviewed literature. It must be noted that *Ecosystem quality degradation* (environmental domain) and *Human health and well-being* (social domain) are 'umbrella' metrics that consolidate aspects which for simplicity and

						End-of-Life Management		
			Feedstock extraction	Processing/ Manufacture	Use (incl. disposal)	Mechanical reprocessing	Composting	Combustion (EfW)
Environmental	-	Global warning potential (GWP)	Controversial (time dependent)	Controversial/Unclear	Controversial/Unclear	Conventional < Bio-based plastics	Controversial/Unclear	Controversial/Unclear
	-	Land use change	Conventional < Bio-based plastics	Not specified	Not applicable	Conventional < Bio-based plastics	Not specified	Not applicable
	-	Ecosystem quality degradation	Conventional < Bio-based plastics	Feedstock dependent	Controversial/Unclear	Conventional < Bio-based plastics	Conventional > Bio-based plastics	Not specified
	-	Fuel depletion potential (FDP)	Controversial/Unclear	Controversial/Unclear	Not applicable	Conventional > Bio-based plastics	Conventional > Bio-based plastics	Controversial/Unclear
	-	Eutrophication	Conventional < Bio-based plastics	Not specified	Not specified	Not specified	Not specified	Not specified
	-	Acidification	Conventional < Bio-based plastics	Feedstock dependent	Not specified	Not specified	Not specified	Not specified
Technical	+	Functionality/ Property superiority	Not applicable	Not applicable	Conventional > Bio-based plastics	Conventional > Bio-based plastics	Not applicable	Conventional = Bio-based plastics
	+	Technological advancement	Feedstock dependent	Conventional > Bio-based plastics	Conventional > Bio-based plastics	Conventional > Bio-based plastics	Not applicable	Conventional = Bio-based plastics
	+	Technical recyclability	Not applicable	Not applicable	Not applicable	Conventional > Bio-based plastics	Conventional < Bio-based plastics	Not applicable
	-	Infrastructure demand	Conventional < Bio-based plastics	Conventional < Bio-based plastics	Conventional < Bio-based plastics	Conventional < Bio-based plastics	Conventional < Bio-based plastics	Conventional = Bio-based plastics
Economical	-	Cost of raw materials (and intermediates)	Conventional < Bio-based plastics	Feedstock dependent	Not applicable	Conventional < Bio-based plastics	Not specified	Not specified
	-	Capital cost	Conventional < Bio-based plastics	Feedstock dependent	Controversial/Unclear	Conventional < Bio-based plastics	Controversial/Unclear	Conventional = Bio-based plastics
	-	Operational/ Maintenance cost	Conventional < Bio-based plastics	Conventional < Bio-based plastics	Conventional < Bio-based plastics	Not specified	Controversial/Unclear	Controversial/Unclear
	+	Revenue from secondary material sales	Not specified	Not specified	Not applicable	Conventional > Bio-based plastics	Controversial/Unclear	Not specified
Social	+	Consumer participation rate	Not applicable	Not applicable	Conventional > Bio-based plastics	Not applicable	Not applicable	Not applicable
	+	Job creation	Conventional < Bio-based plastics	Conventional < Bio-based plastics	Not specified	Not specified	Not specified	Not specified
	-	Human health and well-being	Controversial/Unclear	Controversial/Unclear	Controversial/Unclear	Not specified	Not specified	Not specified
	-	Social function / Equity	Conventional < Bio-based plastics	Not applicable	Conventional > Bio-based plastics	Not specified	Not specified	Not specified

Fig. 3. A bioplastics sustainability matrix presenting the challenges and trade-offs associated with the replacement of conventional (petrochemical-based) plastic with the bio-based alternatives in the food packaging sector, and important knowledge gaps (patterned boxes). The boxes with the texture fill indicate blind-spots of where existing information/data are inconclusive in regards to the sustainability potential of bio-based plastics over their conventional counterparts.

clarity where lumped together. The *ecosystem quality degradation* includes: water consumption, and chemical pollutants that impact on water quality and contribute to ozone-depletion (e.g. chlorofluorocarbons), photochemical ozone formation (e.g. volatile organic compounds), and other pollutant that contribute to ecotoxicy (e.g. polycyclic aromatic hydrocarbons, persistent organic pollutants). The *human health and well-being* include: water security, food security, human toxicity/safety caused by increased release of (toxic) emissions and subsequent impacts on health, local deficiencies.

Claims that bio-based plastics can result to lower environmental impacts compared to their petrochemical counterparts, remain to be verified. As described by Walker and Rothman (WRAP, 2012), using LCA methodologies alone to assess the sustainability of a bio-based alternatives may not reveal all aspects associated with the substitution of petrochemical-based plastics, due to incomparable methodologies or variations in feedstock, production processes, functionality and EoL management. This supports our postulation that the employment of a whole-system based approach like CVORR can highlight hidden impacts and implications in the wider plastic systems (Iacovidou, 2020), and in the sustainability credentials of bio-based food packaging as requested by policy makers (Mutsuga et al., 2008).

5. Conclusions

Replacing petrochemical-based with bio-based plastics is still in its infancy, and comparing the two materials on the basis of selected metrics can lead to misleading interpretations. Petrochemical-based plastics have an established and mature technology for their production and management, while the promotion of bio-based plastics as sustainable alternatives still requires systemic improvements and infrastructure investments. This appears to favor conventional (petrochemical-based) plastics, however looking at the long-term net sustainability potential, infrastructural and economic aspects can be less important. Socio-economic and political aspects will likely have a pivotal role to play in assessing the net sustainability potential of bio-based plastics production, use and management, as well as the boundaries within which sustainability assessments are being performed. Increased land use, related ecosystem destruction and impacts on human health will need to be balanced against poverty alleviation, improved livelihoods, and equity; how do we ensure that people have access to food and water without compromising their livelihoods? How can we generate more bioplastics without affecting the environment and human health? The current low commercialization levels of bio-based plastics (**Column 2**) makes it difficult to estimate with confidence their impacts on human health and safety and ecosystem degradation emerging from the increased demand on land, water and chemicals, such as pesticides and fertilizers required for the extraction of raw materials (van den Oever, 2017; Gironi and Piemonte, 2011). These are some of the 'blind-spots' and potential trade-offs we uncovered in this study, which need to be further investigated.

Our sustainability matrix highlights that there are blindspots, or hotspots (Ögmundarson et al., 2020a), across the entire system and sustainability domains that should be carefully taken into account to ensure a holistic sustainability assessment. It should be emphasized that there is an inherent sensitivity of sustainability impacts that is based on the context, the different types of 1st generation feedstock (upstream of the system) used in bio-based plastics production, and place in which is cultivated, harvested and processed into polymer, and the infrastructure availability for the bio-based plastic packaging management (downstream of the system) that gives rise to blindspots when looking at the sustainability of bio-based plastics from a general perspective. However, the blindspots are quite illuminating on the fact that sustainability cannot not be simply assumed, nor achieved, by replacing petrochemical, fossil based plastics with bio-based alternatives. It requires an in-depth evaluation of the interrelated aspects, i.e. political, environmental, economic, social and technical, and their dynamic relationship in order to arrive to robust conclusions.

The sustainability matrix provides a comprehensive, yet simplified, approach to conceptually assessing the sustainability performance of bio-based plastics, by taking into account all four sustainability domains, i.e., environmental, economic, social and technical, and processes involved in the production-use-management system. Whether the performance of bio-based plastics may or may not be sustainable in each part of the system, be that production or EoL management, is of little importance; as looking at one part of the system fails to depict the whole picture. In the same line, looking at the entire system but focusing only on the environmental or economic performance of bio-based plastics, is also of little importance; as single-dimensional approaches prevent us from looking at the bigger picture. Replacing one material with another in order to bolster sustainability credentials, is not a sustainable practice. Sustainable practice is understanding which packaging components are needed in the food system, and which of these can be replaced by bio-based alternatives, to then holistically evaluate whether bio-based plastic alternatives could perform better than their petrochemical counterparts (in terms of net sustainability benefits) in the long-term, and strike a balance between substitution and complete removal from the system. Such a holistic evaluation is still to be conducted, as the sustainability assessment of bio-based plastics remains an upcoming field of research. From that perspective, the application of holistic sustainability assessment tools leading to a comprehensive legislative framework across the entire lifecycle is to the authors opinion the main route to improve and support the field of bio-based plastics, particularly in food packaging sector. Further research is needed not only to examine the sustainability of different types of 1st generation feedstock used in bio-based plastic packaging production, but also and perhaps most importantly to assess how they compare with alternatives produced using 2nd and 3rd generation feedstocks.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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